Upper critical field of the 122-type iron pnictide superconductors

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Abstract

The upper critical fields (H_{c2}) of the single crystals $(\mathrm{Sr,Na})\mathrm{Fe_2As_2}$ and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ were determined by means of measuring the electrical resistivity, $\rho_{xx}(\mu_0 H)$, using the facilities of pulsed magnetic field at Los Alamos. In general, these compounds possess a very large upper critical field ($H_{c2}(0)$) with a weak anisotropic effect. The detailed curvature of $H_{c2}(T_c)$ may depend on the magnetic field orientation and the sample compositions. We argue that such a difference mainly results from the multi-band effect, which might be modified via doping.

Keywords:
Superconductor, Critical phenomena, Transport properties

1. Introduction

The discovery of high temperature superconductivity in $\mathrm{LaO_{1-x}F_xFeAs}(x = 0.05 - 0.12)$ [1] has stimulated considerable research efforts on the search of new superconducting materials and the elucidation of its pairing mechanism. Resembling the copper oxides, the iron pnictides crystalize in a layered structure and superconductivity occurs upon suppressing the magnetic order either by chemical doping [2, 3] or by applying pressure [4, 5]. However, these new superconductors also exhibit their own unique properties. Instead of a Mott-insulator as observed in cuprates, the parent compounds of iron pnictides are usually bad metals [6]. Furthermore, nearly isotropic superconductivity [7, 8] and three dimensional energy dispersion [9] have been observed in some iron-based superconductors even though they possess a layered crystal structure. These findings are surprising and deserve further research in order to check their generality.

In a multi-band system, the electronic properties might strongly depend on the electron/hole doping level, which would accordingly change the anisotropy of the upper critical field. Experimental confirmation on it might further support the multi-band superconductivity in iron pnictides. Moreover, the value of H_{c2} can be largely enhanced by introducing disorder in a multi-band superconductor, e.g. in $\mathrm{MgB_2}$ [10]. One related question is whether the large $H_{c2}(0)$ observed in iron pnictides is intrinsic or an effect of disorder. Elucidation of these questions would help to catch the intrinsic information of superconductivity in iron pnictides.

Here we report the measurements of magnetoresistance in single crystals of $(\mathrm{Sr,Na})\mathrm{Fe_2As_2}$ and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$. It is indeed found that the upper critical field of all these compounds show rather weak anisotropic effect. The observation of huge $H_{c2}(0)$ (~130T) in $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$, whose sample quality has been improved in comparison with those previously presented in Ref [7], indicates that the large upper critical field is an intrinsic and general feature of iron pnictides.

2. Experimental Methods

Single crystal of $(\mathrm{Sr,Na})\mathrm{Fe_2As_2}$ and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ were synthesized by solid state reaction method using FeAs as flux [11]. The derived crystals were characterized to be a single phase by powder x-ray diffraction (XRD) with Cu $K\alpha$ radiation at room temperature. The doping concentration of K in $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ is nominal value.

The electrical resistance at zero field, $R(T)$, was measured with a Lakeshore ac resistance bridge. The magnetic field dependence of the resistivity, $R_{xx}(H)$, was measured up to 60T using a typical 4-probe method in a capacitor-bank-driven pulsed magnet. The data traces were recorded on a digitizer using a custom designed high-resolution, low-noise synchronous lock-in technique. In order to minimize the inductive heating caused by a pulsed magnetic field, small crystals with typical size 2mm×0.5mm×0.1mm were cleaved off along the c-direction from the as-grown samples.

3. Results and Discussion

Fig.1 shows the electrical resistance at zero field for $(\mathrm{Sr,Na})\mathrm{Fe_2As_2}$(#N1) and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$, respectively. It is noted that no anomalies of structural/magnetic phase transitions are visible at high temperature, suggesting that these samples are likely located in the optimal doing region.The superconducting transition temperature, determined from the mid-point of the superconducting transition, gives $T_c = 27.6$K and 36.8K

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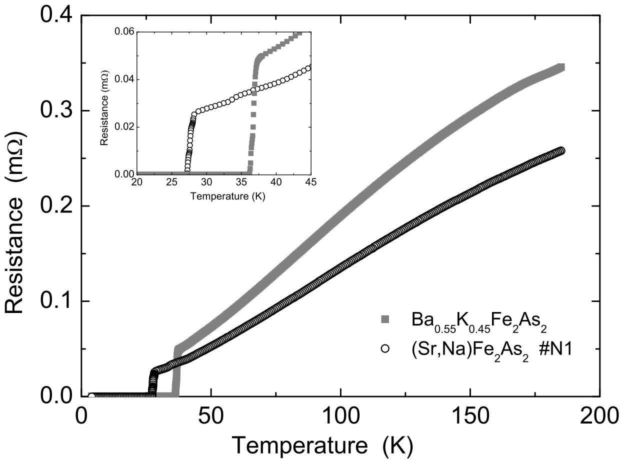

Figure 1: Temperature dependence of the electrical resistance for $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$ (#N1) and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$, respectively. The insert enlarges the section at the superconducting transition.

for $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$(#N1) and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$, respectively. The sharp superconducting transitions (see the inset of Fig.1) indicate a good sample quality for both $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$(#N1) and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$. In comparison with those samples reported in Ref [7], $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ studied here shows a higher T_c and a larger value of residual resistivity ratio (*RRR*), further supporting the improvement of sample quality.

The evolution of superconductivity with magnetic field is shown in Fig.2 and Fig.3 for $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$(#N2) and $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$, respectively. In both figures, the top panel (a) is for magnetic field in the ab-plane and the bottom one (b) is for field along the c-axis. Obviously, the superconducting transition is shifted to lower temperature upon applying a magnetic field. In the case of $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$, the critical field required to suppress superconductivity is slightly different for the two magnetic field orientations applied along the c-axis and the ab-plane, but superconductivity in $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ is not yet suppressed even by applying a field of 60T. The much higher critical field in the K-doped material is likely attributed to its much higher T_c.

Fig.4 shows the scaled upper critical field, H_{c2}/T_c^2, as a function of reduced temperature, T/T_c, for (a) $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$ and (b) $(\mathrm{Ba},\mathrm{K})\mathrm{Fe_2As_2}$, respectively. Here the value of H_{c2} at each temperature is determined from the 50% drop of its normal state resistivity just above T_c. The superconducting transition temperatures (T_c), obtained from the temperature dependence of the electrical resistivity at zero field, are shown to be 27.6K (#N1) and 14.8K (#N2) for $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$; 36.8K (#K1) and 28.2K (#K2) for $(\mathrm{Ba},\mathrm{K})\mathrm{Fe_2As_2}$, respectively. It is noted that the sample #N1 was unfortunately broken while changing the field orientation to $H \parallel ab$ and, therefore, only the data with magnetic field applied along the c-axis is shown. The upper critical fields for sample $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$ (named as #K1 here), as well as the one reported in Ref [7] (sample #K2), are included in Fig. 4(b). From Fig. 4, one can see that the upper critical fields of these two compounds show good scaling behavior with T_c, indicating that the large upper critical field is

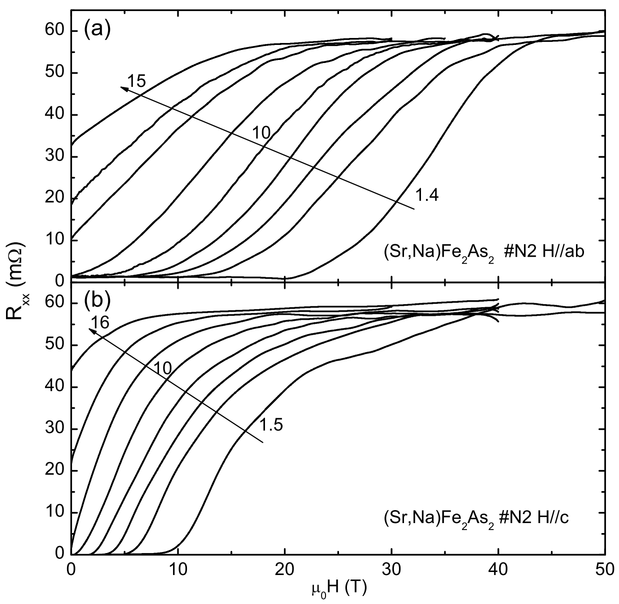

Figure 2: Magnetic field dependence of the electrical resistance at variant temperatures for $(\mathrm{Sr},\mathrm{Na})\mathrm{Fe_2As_2}$ (#N2). (a) $H//ab$ and T=1.4K, 4.7K, 6K, 8K, 10K, 12K, 13K, 14K, 15K; (b) $H//c$ and T=1.5K, 4K, 6K, 8K, 10K, 12K, 14K, 16K (from bottom to top).

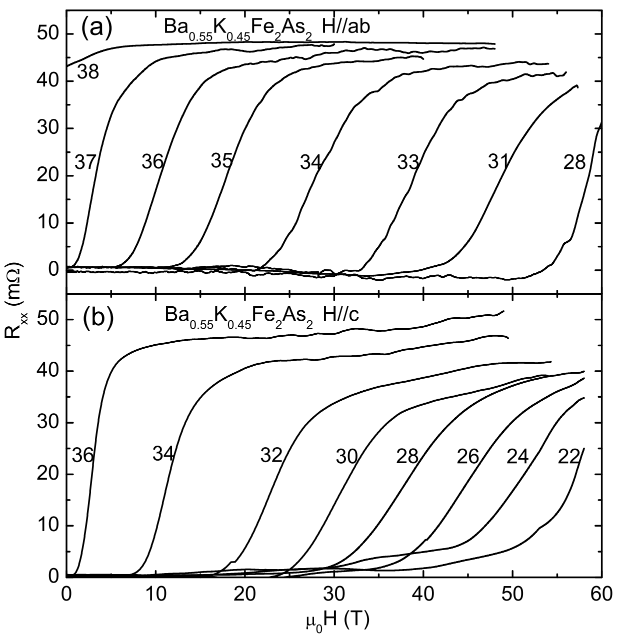

Figure 3: Magnetic field dependence of the electrical resistance at variant temperatures for $\mathrm{Ba_{0.55}K_{0.45}Fe_2As_2}$: (a) $H//ab$ and (b) $H//c$. The temperatures are labeled in the figure with a unit of Kelvin.

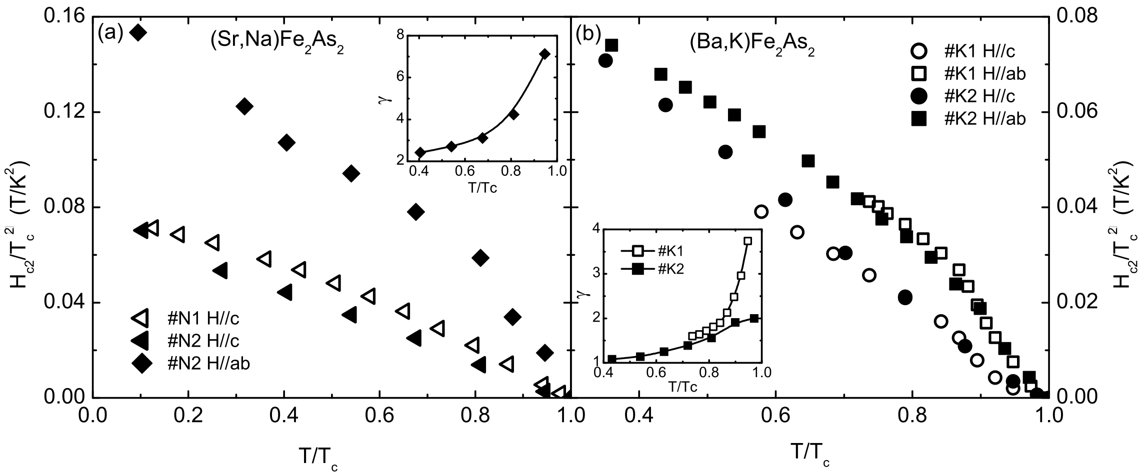

Figure 4: The upper critical field of (Sr, Na)Fe_2As_2 (#N1, #N2) and (Ba, K)Fe_2As_2 (#K1, #K2) versus reduced temperature for $H//c$ and $H//ab$, respectively. The insets show their anisotropic coefficient (γ) versus temperature. Note that the sample #K1 and #K2 refer to $Ba_{0.55}K_{0.45}Fe_2As_2$ measured here and the one reported in Ref. [7], respectively.

an intrinsic feature of the iron pnictides. In this case, the actual upper critical field may strongly depend on the superconducting transition T_c and, therefore, on the sample compositions or sample quality. For example, the upper critical field $H_{c2}(0)$ of $Ba_{0.55}K_{0.45}Fe_2As_2$ (#K1) is determined as 130T according to the scaling behavior together with inputs of $H_{c2}(0)$ = 70T and T_c = 28K from sample #K2 [12]. Such a large $H_{c2}(0)$ far exceeds the weak-coupling Pauli paramagnetism limit, given by $H^p_{c2} = 1.86T_c = 68$T, which might indicate an unconventional type of superconductivity in iron pnictides. Whether the large upper critical field is attributed to the Pauli paramagnetism [12] or the orbital effect [7] remains unclear. However, the weak anisotropy of $H_{c2}(T_c)$ seems to support the later as argued in Ref. [7].

The anisotropic coefficient γ, defined as $\gamma = H^{H\|ab}_{c2}/H^{H\|c}_{c2}$, is plotted in the insets of Fig. 4. One can see that, in all these 122 compounds, the value of γ decreases monotonically with decreasing temperature, showing rather weak anisotropy at low temperatures. Such a weak anisotropy of $H_{c2}(T_c)$ is remarkably distinct from those shown in the high T_c cuprates and the organic superconductors [13, 14]. The curvatures of $H_{c2}(T_c)$ in (Sr, Na)Fe_2As_2 and (Ba, K)Fe_2As_2 are somewhat different (see Fig. 4): in the former one (sample #N2), the upper critical field shows linear temperature dependence for fields applied either in the ab-plane or along the c-axis, but the two curves of $H_{c2}(T_c)$ merge together at low temperature in the later compound. Evidence from both experimental measurements [15, 16] and band structure calculations [17] has shown that the iron pnictides are multi-band systems, consisting of electron pockets and hole pockets. Doping of holes in the compounds as studied here would modify the electronic structure and, therefore, change the detailed temperature dependence of the upper critical field. The slightly distinct anisotropic behavior of $H_{c2}(T_c)$ in these two compounds might be attributed to the variant doping levels as what we also observed in Ba(Fe,Co)$_2$As$_2$ [18]. It is noted that a pronounced upturn curvature is observed near T_c in $Ba_{0.55}K_{0.45}Fe_2As_2$, which might originate from the multi-band effect of the system as well.

Based on the results measured here for the hole-doped compounds and those previously investigated for the electron-doped compounds [19, 20], weak anisotropy of superconductivity seems to be a general feature of the iron pnictides, in particular for the 122-system and the 11-compound. The anisotropic properties are usually determined by the underlying electronic structure, which was found to be rather two dimensional in cuprates and organic superconductors [13, 14]. However, our measurements indicate that the electronic structure of the iron pnictides might be more like three dimensional [7], which has been confirmed by recent ARPES measurements [9, 21]. All these suggest that the inter-layer coupling would play an important role in understanding the mechanism of superconductivity.

We would also like to point out that the weak anisotropic and large upper critical field are unique features of the iron-based superconductors, which will make them very promising materials for future applications.

4. Conclusion

In summary, we have determined the upper critical fields $H_{c2}(T_c)$ of (Sr, Na)Fe_2As_2 and $Ba_{0.55}K_{0.45}Fe_2As_2$ by measuring the electrical resistivity in a pulsed magnetic field. It was found that these compounds show large values of $H_{c2}(0)$ and relatively weak anisotropy of superconductivity at low temperature in general. The upper critical fields obtained from variant samples can be well scaled with its superconducting transition T_c.

5. Acknowledgements

This work was supported by NSFC (No. 10934005), the National Basic Research Program of China (No. 2009CB929104), the PCSIRT of the Ministry of Education of China, Zhejiang

Provincial Natural Science Foundation of China and the Fundamental Research Funds for the Central Universities. Work at NHMFL-LANL is performed under the auspices of the National Science Foundation, Department of Energy and State of Florida.

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